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Original Article

Process Design and Performance Analysis of Mixed Model Assembly Line Using Analytical and Discrete Event Simulation Method

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Abstract - *The assembly line in any manufacturing industry serves the utmost importance in the entire manufacturing system as it represents the final production of the factory floor. The rate of production of industry is governed by the cycle time at the bottleneck station. Therefore, the cycle time analysis of the assembly line using standard work measurement techniques is of utmost importance for assessing the productivity of the shopfloor. In order to address the ever-increasing demands of capacity, the systematic methodology for work measurement, process design and two-sided mixed-model assembly line balancing (TSMMALB) has been proposed. Initially, the analytical model was presented to evaluate the performance parameters of the assembly line. The assembly line balancing problem was systematically analysed using industrial engineering techniques of time study, and the corresponding balancing of work elements was performed using the Ranked-Positional Weighs Method (RPWM). The number of workstations required to design an assembly line was kept fixed in accordance with the cycle time requirements. The problem was further extended to multi-objective genetic optimization (MOGA) of the assembly line with objectives of minimizing cycle time and workload variation and maximizing the throughput in terms of line efficiency. The entire cycle time measurement was performed by Predetermined Motion Time Systems (PMTS) as an established work measurement standard. The hypothesis test of cycle time against models was performed to analyse variations in the means and standard deviations of cycle times by Analysis of Variance (ANOVA) using MINITAB© statistical software. In the last part of the paper, discrete event simulation of the process was performed using AnyLogic© software. The simulation provided comprehensive results of standard productivity Key Performance Indicators (KPI), including mean flow times and capacity utilization, to evaluate the pace of the manufacturing system. In future, the correlation between the mathematical model and the discrete event model can be investigated for hybrid-flexible assembly systems*.

Keywords - *Assembly systems, Line balancing, Hypothesis testing, Optimization, Discrete event simulation*.

1. Introduction

Assembly is the final step in the manufacturing of complex products, utilizing up to 40% of production time and accounting for up to 20% of overall cost and 20-60% of labour cost associated with production [1]. Assembly system design for typical manufactured goods in this context, referred to as industrial assembly, is driven by an increased number of product varieties, resulting in increased complexity of both product and assembly processes as demand and global product competition increases [2]. This leads to an increase in the rate of reconfigurations. As far as the production and capacity enhancement needs of factories are concerned, the deployment of flexible, modular architecture of manufacturing and assembly systems capable of multi-product processing and minimum setup time is of utmost importance. Various direct and indirect methods of flexible assembly and manufacturing systems design through operational sequencing, line balancing, process optimization, and simulated modelling of FMAS (Flexible Manufacturing and Assembly Systems) with the use of DES (Discrete Event Simulation), MBSE (Model Based Systems Engineering) and OAL (Optimization Algorithms) have been widely studied and explored by researchers, manufacturing, and industrial engineers around the globe in past years. The studies produced by these communities have been consolidated and presented in the literature review below.

Pattnaik et al. [1] presented the hybrid architecture of RAS (Reconfigurable Assembly System) for the dynamic scheduling purpose. The architecture was based on multiagent systems. The protocol dynamically assigns operations to the resources of the assembly system to achieve system reconfiguration. The work presented by Sirin et al. [2] consists of a methodology for the design of product family and reconfiguration of assembly systems simultaneously over several product generations. The products and assembly system were assumed to be modular and reconfigurable, respectively. The paper by Joseph et al. [3] discussed the optimization of a mixed-model assembly line with two objectives: minimization of setups and variation of production rates using a non-dominated ranking genetic algorithm. They also compared the optimal results with those from the total enumeration scheme. Hu et al. [4] explained the hardware design of a reconfigurable assembly system to accommodate a product family. A reconfigurable pallet-based approach was introduced to achieve mixed model assembly. Guido et al. [5] have introduced Reconfigurable Manufacturing Systems (RMS) as a solution that combines both DMLs' (Dedicated Manufacturing Lines) throughput and FMS' (Flexible Manufacturing Lines) flexibility. Suitable buffers and parallelization of machines allow the decoupling of the system's cycle time and cycle time for each individual workstation. Research on RMS has covered balancing and possible configurations and their impact on productivity. TAKT (Total Activity Completion Time) decisions for the planning of MMALs (Mixed Model Assembly Lines) have been presented by Zhang et al. [6].

In MMALs planning, takt time is a time unit at which a product must be produced to match the speed required for the product. Fantahun et al. [7] proposed a multi-objective model and a heuristic algorithm to simultaneously solve the balancing and sequencing problems in the U-shaped assembly line. The use of DES (Discrete Event Simulation) for the production line balancing was presented by Zupan et al. [8] for the optimization of the production line. First, the basic theory and steps for the production line balancing were presented. Gingu [9] presented a central theme of research on industrial engineering, which has as its main objective the optimization of the flows in a flexible manufacturing system by configuring the workstations required and the dynamic control of the rhythm and the manufacturing stocks based on modelling discrete event systems. The work presented by Digalwar [10] utilized simulation as a decision-making tool in a complex manufacturing setup. A vehicle assembly line at an automobile company in India was modelled and analyzed to help managers identify the criticality of different parameters. Conveyor speed, operator fatigue and incoming material quality were selected from a pool of parameters which affect the line output. The case study on car exhaust system fabrication line was presented by Hanesh et. Al. [11], wherein the Maynard Operation Sequencing Technique (MOST) has been used as a standard work measurement tool for cycle time analysis of various operations and line balancing. The work presented by Vikram et al. [12] focused on the reduction and elimination of Non-Value Adding (NVA) activities at the vehicle body panel assembly line by establishing time standards using MOST. Some of the NVAs were eliminated, and the cycle time of various operations was reduced by designing an improved process by means of fixturing and tooling, resulting in a 41% reduction in assembly time. The establishment of recommendations for standard time, manpower planning, utilization, and elimination of unproductive activities at the tractor assembly line was presented by Meshram [13]. The work presented by the authors highlighted the development of methodology for minimization of NVAs and operator fatigue on the manufacturing line with the help of the Maynard Operation Sequencing Technique. The concept of simulation-aided assembly line balancing using Discrete Event Simulation (DES) was presented by Doung [16]. Multiple layouts of assembly lines, such as parallel, U-shaped, and parallel U-shaped, were considered for the study and simulation was performed through ARENA© software. The analysis of shopfloor performance through discrete event simulation was studied by Yeong [17].

The work presented a case study of the semiconductor manufacturing industry. The punching department was modelled to investigate the effect of shopfloor changes on production performance through simulation modelling. A mathematical model for assembly line balancing problems under ergonomic workload constraints was explored by Polat [18]. The main objective behind this work was to balance the cycle time against TAKT and the physical workload of the stations simultaneously. A case study on the optimization of assembly line performance by Method Time Measurement (MTM) standard and simulation was presented by Breznik [19]. Ala [20] has presented a combined approach to automotive assembly line design using lean manufacturing tools and line-balancing algorithms. Various methods for mixed-model assembly line balancing were presented by Reginato [21], wherein the heuristic algorithm was developed to balance the production line with multiple models. In the work reported by Hamazadayi [25], a Simulated Annealing (SA) algorithm has been developed to simultaneously balance and re-sequence the mixed-model U-shape assembly lines.

The integrated solution approach for real-time launch control of models on mixed-model assembly lines has been presented by Bock [26]. The work provided a sophisticated optimization approach considering both the workflow of an assembly line as well as the part feeding process. The real-time approach was tested in a simulation study to compare with alternate launching approaches. Lopes et al. [27] presented a Mixed-Integer Linear Programming (MILP) based optimization approach for balancing mixed-model assembly lines for workload balancing and operation sequencing across workstations. The research presented by Liu [28] utilized uncertainty theory to model uncertain demand and introduced complex theory to measure uncertainty in mixed-model assembly lines. A simulation modelling based approach for balancing automotive component manufacturing lines has been put forward by Jamil [31].

In this work, the analytical model for performance analysis of two-sided mixed-model assembly lines has been established. The work presented is the first attempt to report the mathematical analysis and line balancing of a two-sided assembly line wherein work elements are added to each station from both sides. The process design and performance analysis aim at productivity improvement, which has been addressed by line balancing presentation by Ranked Positional Weighs Method (RPWM) against cycle time and TAKT (Total Activity Completion Time) requirements. The analytical model was supplemented by Discrete Event Simulation (DES), which also shows how simulation modelling can be helpful in monitoring and analyze productivity Key Performance Parameters (KPIs).

The remainder of this paper is organized as follows: Section 2 briefly presents the mathematical formulation of performance parameters of the two-sided mixed-model assembly line in terms of cycle time analysis, line balancing algorithm representation, as well as variable base part launching rate on the assembly line. Section 3 explains the standard work measurement technique PMTS followed for cycle time data collection on the factory floor. A representation of the bi-objective optimization problem is provided in section 4. The basic setup of discrete event simulation is described in section 5. Section 6 provides the results of the hypothesis test and computational results of line balancing and optimization and discusses the Discrete Event Simulation method. Section 7 concludes the paper.

2. Materials and Methods

2.1. Assembly Line Performance Parameters

Analytical modelling of an assembly line has been performed to understand how the change of one variable affects other variables and interdependencies between input-output variables. The model has been developed and presented for a straight assembly line with serial stations only (no parallel stations). The initial part of the analytical model considers performance parameters of line, line balancing algorithms, constraints and other factors like repositioning losses, zonings, and ergonomic and gender-neutral stations. The time-distance relationship and its effect on part feed rate on the main assembly line, as well adaption of pre-assembly / sub-assembly of parts or converting unconstrained online work content into offline work content, has also been considered. Figure 1 shows the schematic representation of the two-sided serial layout of an assembly line for which the model has been developed. In the later stage, a multi-objective optimization algorithm comprising of simple mathematical formulation has been developed to further analyze the multi-model line balancing problem in terms of optimizing resource utilization.

Various notations used in the model and shown in the above representation are as follows:

T_{w_e} = Elemental time of processing work element 'e' on given workstation (min), where e = 1… n

T_{S_i} = Total time of '$i^{th'}$ workstation where, i = 1… N (min)

N = Total number of workstations

L_{S_i} = Length of the '$i^{th'}$ workstation (m)

L_{S_p} = Center to center distance between two consecutive workstations (m)

L_{S_a} = Total length of the assembly line (m)

w_{e_i} = Work element to be processed on '$i^{th'}$ workstation

Op_i = Operator/worker on '$i^{th'}$ workstation

v_c = Speed of the conveyor (m/min)

T_{w_e} = Elemental time of processing work element 'e' on given workstation (min), where e = 1… n

∴ Total workstation time for '$\boldsymbol{i^{th'}}$ workstation can be expressed as,

$$T_{S_i} = \sum_{i=1}^{n} T_{w_{e_i}} \tag{1}$$

Let TWC = Total Work Content of processing 'n' work elements (operations) on 'N' workstations.

$$TWC = \sum_{i=1}^{N} T_{S_i} \tag{2}$$

Maximum available time for activity completion (TAKT) for a given line can be expressed as,

$$N \times T_{cycle} = \sum_{i=1}^{N} T_{S_{imax}} = TAKT \tag{3}$$

Let, T_{idle} = Idle time of the given assembly line can be mathematically expressed as,

$$T_{idle} = \sum_{i=1}^{N} \left(T_{S_{imax}} - T_{S_i}\right) \tag{4}$$

Efficiency of the assembly line can be expressed as,

$$\eta_{line} = \frac{TWC}{N \times T_{cycle}} = \sum_{i=1}^{N} \left(\frac{T_{S_i}}{T_{S_{imax}}}\right) \tag{5}$$

Balance Delay (BD) as a function of line efficiency can be expressed mathematically as,

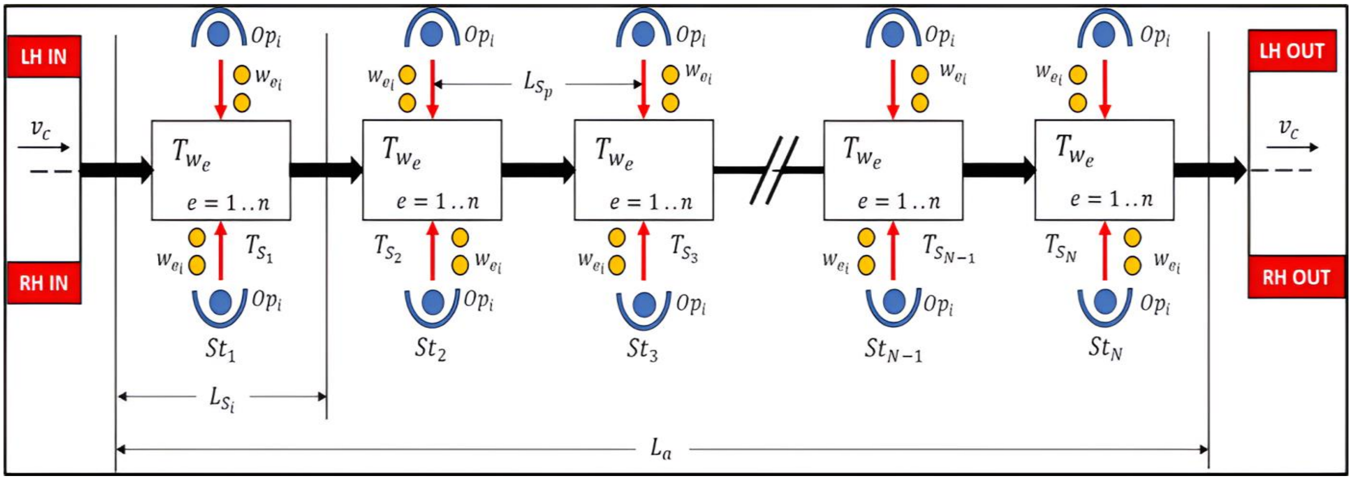


Fig. 1 Schematic representation of an analytical model of the assembly line.

$$BD = \frac{[(N \times T_{cycle}) - \text{TWC}]}{(N \times T_{cycle})} = 1 - \eta_{line} \qquad (6)$$

The above Equations (1) to (6) represent the basic performance analysis parameters of the assembly line and serve as a baseline or starting point for cycle time analysis and workload balancing in an assembly line design. The line balancing model has been presented below.

2.2. Assembly Line Balancing Algorithm

The objective of line balancing is to equally distribute the work content on each individual workstation to get rid of bottlenecks and forced idleness in operations/operators. The objective function of line balancing in alternate equivalent forms can be mathematically expressed as:

$$\text{Minimize} \sum_{i=1}^{N} (T_{s_{imax}} - T_{s_i}) \qquad (7)$$

Subject to:

1. $\sum_{e \in i} \left(T_{w_{e_i}} \leq T_{s_i}\right)$ For 'i^{th}' workstation where, $i = 1 \dots N$

2. All the precedence constraints are obeyed.

The basic algorithms for assembly line balancing are the Largest Candidate Rule (LCR), Kilbridge and Wester Method (KWM) and Ranked Positional Weights Method (RPWM). In the presented work, the RPW method has been used for line balancing analysis and assignment of tasks on the workstations in accordance with their cycle times against TAKT. Apart from line balancing, other physical factory floor space utilization considerations such as the workstation pitch, total assembly line length and its effect on work part feeding rate have also been considered while developing a model. Time-distance relationships, manpower planning and % utilization against TAKT time, as well as static/variable rate of base-part launching at the starting point of the assembly line, have also been considered in a further section of the model.

2.3. Other Considerations in Assembly Line Process Design

On each production line, some time is required for operators to reposition from one station to another station which is time lost in repositioning. Let, T_r = Time required at each cycle to reposition the operator. Therefore, the maximum allowable cycle time 'T_s' for the station can be mathematically represented as,

$$T_s = T_{s_{imax}} \leq (T_{cycle} - T_r) \Rightarrow T_{s_i} \leq \sum_{i=1}^{N} (T_{s_i}) - T_r \qquad (8)$$

The total length of the assembly line, distance between two consecutive stations and cycle time also influences the part feed rate on the line, which has been presented by the time-distance relationship. The common mode of transport on manual assembly lines is the constant-speed conveyor. The relationship that has been established between the speed of the conveyor, part feed rate, workstation and total assembly line length has been presented below.

For the workstation to have a length L_{s_i}, wherein $'i'$ denotes the workstation, $i = 1\dots N$,
Total length of the assembly line can be expressed as,

$$L_a = \sum_{i=1}^{N} L_{s_i} \qquad (9)$$

And $L_a = N \times L_{s_i}$ when all L_{s_i} are equal.

For the part feed rate 'f_p,' operation cycle time T_{cycle}, the center-to-center distance between workstations as a function of velocity 'v_c' of constant speed conveyor can be expressed as,

$$L_{s_p} = \frac{v_c}{f_p} = v_c \times T_{cycle} \quad (10)$$

The mathematical formulation of the required number of operators and their work utilization on each station against TAKT has been provided below. For a manual assembly line with LH & RH work content, an ideal situation is to deploy equal manpower on both sides, considering equal line balance utilization. However, due to various losses on the line, unequal (60/40) utilization leads to additional manpower that can be mathematically expressed as,

$$M_T = \frac{Op_f + \sum_{i=1}^{N} Op_i}{N} \quad (11)$$

Where, M_T is total manning level, Op_i is operator on $'i^{th'}$ workstation, Op_f is flexible/additional manpower, and N is the total number of workstations. Manpower % utilization can be evaluated as,

$$\%M_U = \sum_{i=1}^{N} \left(\frac{T_{s_i}/Op_i}{T_{s_{imax}}} \right) \times 100 \quad (12)$$

For the single/batch model assembly lines, the base parts are launched at the beginning of the line at a fixed rate as a function of cycle time. 'T_{cycle}.' In the case of mixed-model line, the time of launching is more complicated because each model is likely to have different total work content *'TWC'* workstation time $'T_{si}.'$ Hence, it can be inferred that the time interval between launches and which model to select are independent. For a mixed-model assembly line, a static base-part launching rate cannot be preferred as every different model has different total work content, even though TAKT time is constant for the line. Hence, a variable launch rate needs to be used in such cases. In variable rate launching, the time interval between the launching of the current base part and the next is set as a function of the total work content time of the currently launched model. Variation in work content leads to variation in cycle time per workstation of the launched model.

$$T_{L_j} = \frac{TWC_j}{N \times \eta_r \times \eta_{line}} = \frac{\sum_{i=1}^{N} Ts_{j_i}}{N \times \eta_r \times \sum_{i=1}^{N} \left(\frac{T_{s_i}}{T_{s_{imax}}} \right)} \quad (13)$$

T_{L_f}= Time interval between launches in fixed-rate launching (min)

R_p = Total production rate of all models in a schedule where models range from j = 1… m

TWC_j = Total work content time of model 'j' (min)
η_r = Repositioning efficiency
η_{line}= Line balancing efficiency
Ts_{j_i}= Workstation time of model 'j' for '$i^{th'}$ workstation, where i = 1… N (min)

As far as fixed-rate launching of the base part on the first workstation of the assembly line is concerned for single or batch-model lines, the time interval between the launching of the current base part and the next is constant. The time interval is set as a function of conveyor speed, center-to-center distance between work parts and production rate. However, the launch schedule must be kept consistent with respect to the time and available manpower on the line.

3. Standard Work Measurement

3.1. Predetermined Motion Time System (PMTS)

The Predetermined Motion Time System (PMTS) satisfies the work measurement technique in the manufacturing arena. It is the widely used technique of work measurement established in industries. In the presented work, the cycle time measurement of various fitment operations on the main assembly line was performed with the help of the PMTS tool. This tool assists in the work measurement of operations wherein cycle time is evaluated as a function of action distance, body motion, control over parts/objects and alignment activities performed by the operators on the assembly line. In the basic most analysis, three models are defined according to the nature of activities being performed at the production facilities or assembly lines [11]. These models are defined based on the movement of the object, constraints on the free space motion of the object and whether the assisting tool/s are used for the accomplishment of the activity. These models are classified as General Move Sequence Model, Controlled Move Sequence Model and Tool Use Sequence Model.

The general move model is for a displacement of the object in free space (spatial motion in the air). For the controlled move model, the movement of an object when it remains in contact with a surface or is attached to another object during the movement. The tool use sequence model is specifically for the use of common hand tools. However, the Tool Use sequence model does not define a third basic activity - normally, it is a combination of General Move and Controlled Move activities. The common scale of index numbers for all PMTS sequence models is 0, 1, 3, 6, 10, 16, 24, 32, 42 and 54. The time value for a sequence model in basic PMTS is obtained by simply adding the index numbers for individual sub-activity and multiplying the sum by 10. The PMTS time is measured in Time Measurement Units (TMU), wherein 1 TMU equals 0.036 seconds. Table 2 shows a generic representation of basic PMTS models used for cycle time measurement.

Table 2. Schematic representation of cycle time measurement and verification using PMTS and stop-watch study

PMTS Based Cycle Time Measurement				Stop-Watch Based Cycle Time Measurement				
Op No	**Operations / Fitments**	**TMU**	**Time**	**Start Time**	**End Time**	**Elapsed Time**	**Time**	**Cum. Time**
1	**Main Operation A**	(units)	(minutes)	(minutes)	(minutes)	(minutes)	(minutes)	(minutes)
a	Sub-operation 1	220	0.132	0:00:14	0:00:22	0:00:08	0.133	0.133
b	Sub-operation 2	420	0.252	0:00:23	0:00:39	0:00:16	0.267	0.400
c	Sub-operation 3	50	0.030	0:00:40	0:00:42	0:00:02	0.033	0.433
d	Sub-operation 4	360	0.216	0:00:43	0:00:56	0:00:13	0.217	0.650
e	Sub-operation 5	210	0.126	0:00:57	0:01:04	0:00:07	0.117	0.767
2	**Main Operation B**							
a	Sub-operation 1	2080	1.248	0:01:04	0:02:21	0:01:17	1.283	1.283
b	Sub-operation 2	2470	1.482	0:02:22	0:03:50	0:01:28	1.467	2.750
c	Sub-operation 3	4720	2.832	0:03:51	0:06:44	0:02:53	2.884	5.634
d	Sub-operation 4	10720	6.432	0:06:45	0:13:12	0:06:27	6.450	12.084
e	Sub-operation 5	3200	1.920	0:13:13	0:15:12	0:01:59	1.983	14.068
3	**Main Operation C**							
a	Sub-operation 1	3240	1.944	0:15:13	0:17:10	0:01:57	1.950	1.950
b	Sub-operation 2	4800	2.880	0:17:11	0:20:08	0:02:57	2.950	4.900
c	Sub-operation 3	4960	2.976	0:20:09	0:22:58	0:02:49	2.817	7.717
d	Sub-operation 4	5360	3.216	0:22:59	0:26:15	0:03:16	3.267	10.984
e	Sub-operation 5	2470	1.482	0:26:16	0:27:45	0:01:29	1.483	12.467
4	**Main Operation D**							
a	Sub-operation 1	2080	1.248	0:27:46	0:29:06	0:01:20	1.333	1.333
b	Sub-operation 2	4800	2.880	0:29:07	0:31:54	0:02:47	2.784	4.117
c	Sub-operation 3	5360	3.216	0:31:55	0:35:10	0:03:15	3.250	7.367
d	Sub-operation 4	2470	1.482	0:35:11	0:36:40	0:01:29	1.483	8.851
e	Sub-operation 5	3200	1.920	0:36:41	0:38:36	0:01:55	1.917	10.767

Figure 2 represents a schematic of the cycle time data collection and verification method. The actual cycle time measurement on the assembly line for developing a model was performed in such a way that the cycle time data recorded through PMTS analysis were re-evaluated and validated by stop-watch-based time recording of a minimum of three readings of each operation to ensure accuracy in calculation. Furthermore, the stop-watch time study was validated by video recording of each operation on the assembly line to ensure the foolproofness of the cycle time analysis data used for establishing the baseline of the study. Then obtained, cycle times for each operation were finally added to obtain the Total Work Content (TWC) of the assembly line. After that, basic mathematical calculations were performed to evaluate the required number of workstations for the new assembly line design to distribute work content wherein the RPW method was utilised for Two-Sided Mixed-Model Assembly Line Balancing (TSMMALB). The basic calculations performed for model input and precedence constraints diagram of both left and right side work elements have been discussed in the further section.

3.2. Cycle Time Analysis

The cycle time data of the existing assembly line was collected and validated with the help of PMTS and stopwatch-based time study, respectively, as aforementioned. For designing the new assembly line for raised customer demand, certain calculations on the input data were made to evaluate the total number of workstations required and the maximum available cycle time or TAKT time of the new line. The Net Effective Shift Time (NEFT) in which the assembly line will be operating was considered to be 455 minutes after subtracting breaks for operators and morning meetings during the total shift of eight hours. The demand for which the line will be designed to operate and assemble the products was considered as 6 per shift. Hence, the total activity completion time or TAKT of the line was found out to be NEFT/Customer demand, which is 455 minutes/6 products per shift, which equals 76 minutes. Now, as far as the practicality of the assembly line operation is concerned, various losses in terms of machine downtimes, productivity loss due to Non-Value added Activities (NVA) or quality losses / in-process defects need to be considered. Hence, Overall Equipment Efficiency

(OEE), which is the product of availability, productivity and quality, was considered to be 85% for the new line. Apart from OEE, another important factor that needs to be considered is Line Balancing Utilization (LBU). This factor has been taken into account because the model presented in the work is for a two-sided assembly line wherein work parts are fed from both left and right sides. Therefore, it is not necessary that the work-parts added from both sides have the same Design for Assembly (DFA) all the time. In order to take this stochastic nature into consideration, a 5% loss in LBU, that is, 95% utilization, is considered. Therefore, the target TAKT time within which the new assembly line will be operating was calculated as a product of actual TAKT (76 minutes), OEE (85%) and LBU (95%), which was found to be 61 minutes. The physical significance of this calculation is that one product on the main assembly line will move from one workstation to the next in 61 minutes. Now, for the last part of calculating the total number of required workstations, the total work content of the assembly line operations was calculated to be 1071 minutes from PMTS and the stop-watch-based time study method. Therefore, the total number of required workstations was calculated as total work content/target TAKT time, which was multiplied by a factor of 0.6 to consider 60:40 line balance utilization. Hence, the total number of required workstations for which line balancing was performed was 10 workstations.

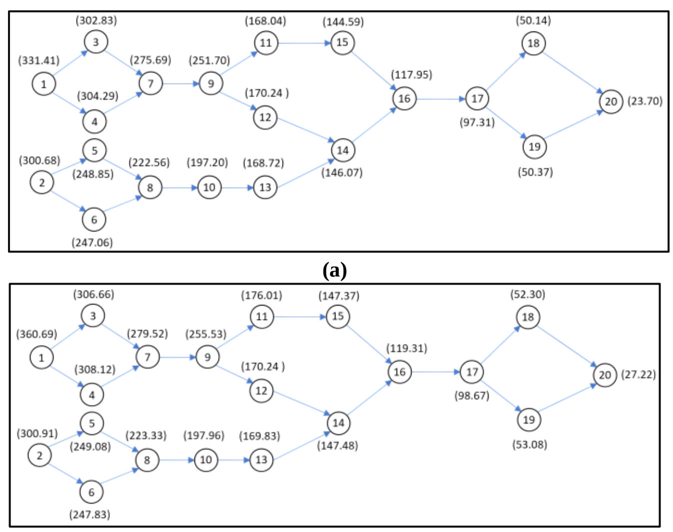
Table 1. Cycle time data for left-side work content of Model A, B, and C

Work Elements	CT (A)	CT (B)	CT (C)	Precedence
1	25.44	22.93	25.44	-
2	27.33	22.53	27.33	-
3	27.13	24.34	27.13	1
4	28.60	28.60	28.60	1
5	25.75	23.23	26.54	2
6	24.50	23.00	26.66	2
7	23.99	21.00	26.55	3,4
8	25.36	24.56	26.76	5,6
9	28.60	25.65	28.60	7
10	28.14	25.43	28.32	8
11	28.64	26.00	25.87	9
12	22.76	20.89	26.15	9
13	22.35	21.45	25.00	10
14	28.17	25.45	28.23	12,13
15	28.05	26.78	27.56	11
16	20.65	20.20	25.45	14,15
17	20.50	20.32	24.67	16
18	25.08	24.55	27.89	17
19	25.86	24.00	25.88	17
20	27.22	25.00	28.32	18,19

In Figures 3 (a) and (b) of precedence constraint diagrams of left and right side work contents, respectively, the driving factor of the RPW algorithm of line balancing is denoted in round braces outside the work element number. The main factor of this method, which runs the algorithm, is Ranked Positional Weight (RPW), which is calculated by adding the cycle times of all the successive work elements which are directly connected by an arrow except the work element for which RPW is being calculated.

Table 2. Cycle time data for right-side work content of Model A, B and C

Work Elements	CT (A)	CT (B)	CT (C)	Precedence
1	25.44	23.07	25.44	-
2	27.33	24.56	27.33	-
3	27.13	25.66	27.13	1
4	28.60	28.60	28.60	1
5	26.29	25.76	27.54	2
6	24.50	23.00	25.66	2
7	24.0	26.20	25.55	3,4
8	25.36	22.76	26.76	5,6
9	28.60	27.60	28.60	7
10	28.48	27.65	28.48	8
11	23.45	24.45	25.44	9
12	26.95	25.95	27.69	9
13	22.65	20.13	24.45	10
14	28.12	26.89	28.23	12,13
15	26.63	25.00	27.88	11
16	20.65	20.45	25.30	14,15
17	20.50	20.33	24.32	16
18	26.44	27.40	27.00	17
19	26.67	25.54	26.89	17
20	23.70	22.33	25.67	18,19



(a)

(b)

Fig. 2 Precedence constraint diagram of Model A of (a) LH and (b) RH work content

4. Bi-objective Optimization Model

4.1. Assumptions and Functions Definition

There are certain assumptions which are important to be defined well before representing the optimization model, since the operation of the optimization algorithm obeys these assumptions at each iteration stage. The assumptions considered before defining objective and constraining functions are as follows:

1. The similar operations of different models could have different cycle times due to different assembly procedures or fitments, resulting in model inherent variety.
2. The immediate and other precedence constraints of all the models are well known such that the resulting operation sequence of all models constitutes N operations.
3. The setup time during the change of each new model has been calculated in the cycle time of the corresponding model itself.
4. Each operation 'i' has been assigned to a specific workstation 'k' of model 'j' cannot be repeated and reassigned to different stations; however, some different tasks could be assigned to different stations and common tasks to a single station considering the assembly requirements.
5. TAKT time is constant and independent of models and operation sequence.
6. The design of an assembly line is straight and has a serial layout (no parallel workstations).

Various notations used for defining the objective functions and constraining variables are as follows:

CT_T = Total cycle time of the mixed-model (min)

T_{ijk} = Cycle time of operation 'i' for model 'j' on workstation 'k'

δ_{ijk} = Binary operator, if operation 'i' for model 'j' is assigned to workstation 'k', then δ_{ijk}= 1, otherwise δ_{ijk}= 0

i = Index of operation 'i' where i = 1,2…,l

j = Index of model 'j' where j = 1,2…,m

k = Index of workstation 'k' where k= 1,2…,n

$$OF_1: Minimize\ CT_T = \left[\left(\sum_{i=1}^{l}\sum_{k=1}^{n} T_{ik}.\delta_{ik}\right)\right] \tag{14}$$

$$OF_2: Minimize\ WO = \left[max \sum_{k=1}^{n}\left(\sum_{i=1}^{l} T_{ik}.\delta_{ik}\right)\right] \tag{15}$$

Equations (14) and (15) are the main objective functions of the algorithm to minimize the cycle time and work overload, respectively. The constraining variables or functions are represented by Equations (16) and (17) for task assignment constraint and cycle time constraint, respectively. The task assignment constraint ensures each task is assigned to exactly one station. Cycle time constraint ensures that the cycle time of each workstation does not exceed the predefined maximum, that is TAKT time of the line. Apart from these two main constraining functions, workload balancing constraints can be considered in actual practice such that the standard deviation of workload must be greater than the maximum allowable standard deviation. The physical significance of the standard deviation of workload is that the work content must be nearly equally balanced across all workstations without excess capacity or bottleneck stations.

$$\sum_{k=1}^{n} \delta_{ik} = 1 \tag{16}$$

$$\left(\sum_{i=1}^{l}\sum_{k=1}^{n} T_{ik}.\delta_{ik}\right) \le T_{s_{imax}} \tag{17}$$

4.2. Encoding and Decoding

The encoding task attempts to develop a classification of a graph which contains the sequence of operations based on the operation sequencing priority in order to satisfy the precedence constraints. The decoding task essentially takes the values of the operation sequence generated at the encoding stage and assigns them to the workstations. Each solution or population generation of an individual algorithm executes encoding and decoding tasks for operation sequencing and assignment to the respective workstations. The encoding and decoding flowchart is represented in Figures 4 (a) and (b), respectively. Let, $\boldsymbol{\phi} = [\mathbf{1}, \boldsymbol{l}]$ be the solution vector for a number of operations, where operations range from $\boldsymbol{i}$ = 1,2…,$\boldsymbol{l}$ and $\boldsymbol{\phi_i}$ is a priority vector for $\boldsymbol{i^{th}}$ operation. Let, $\boldsymbol{g} = [\boldsymbol{T}, \boldsymbol{S}]$ be the graphical form of a precedence constraint diagram. Where $\boldsymbol{T}$ is the set of tasks/operations at each node, and $\boldsymbol{S}$ is the relation between each operation based on their sequence. Let $\boldsymbol{Z}$ be the set of operations and $\boldsymbol{Z'}$ be the subset of $\boldsymbol{Z}$. The decoding method assigns operation sequence to the workstations wherein $\boldsymbol{N}$ are the maximum number of workstations.

4.3. Chromosome representation – crossover & mutation

For a multi-objective genetic optimization aimed at minimizing cycle time and workload variation, each solution was represented as a set of chromosomes containing genetic information which represents different parameters. Each chromosome of the first gene contains information representing the total number of workstations, and another gene represents workload variation across the workstations. The representation of chromosomes contains two distinct operators, namely crossover and mutation operators. Each constraining parameter other than workload variation or number of stations can be represented by different genes.

The random substrings were selected to represent the chromosome in Figures 5 (a) and (b) for multi-point crossover and swappable mutation operators, respectively.

A crossover operator ensures that offspring maintains a balanced distribution of tasks across the total number of assembly workstations to minimize the total workload variation. The mutation operator was designed to introduce small changes in genetic material. To minimize cycle time and the number of workstations, the mutation operator focuses on merging adjacent workstations or splitting overloaded or bottleneck workstations intelligently. Mutation operators can also involve reassigning operations between workstations in such a way that it can minimize workload variation or overload. Therefore, in this way, each chromosome in the total population is a combination of genes aiming to minimize both objective functions simultaneously.

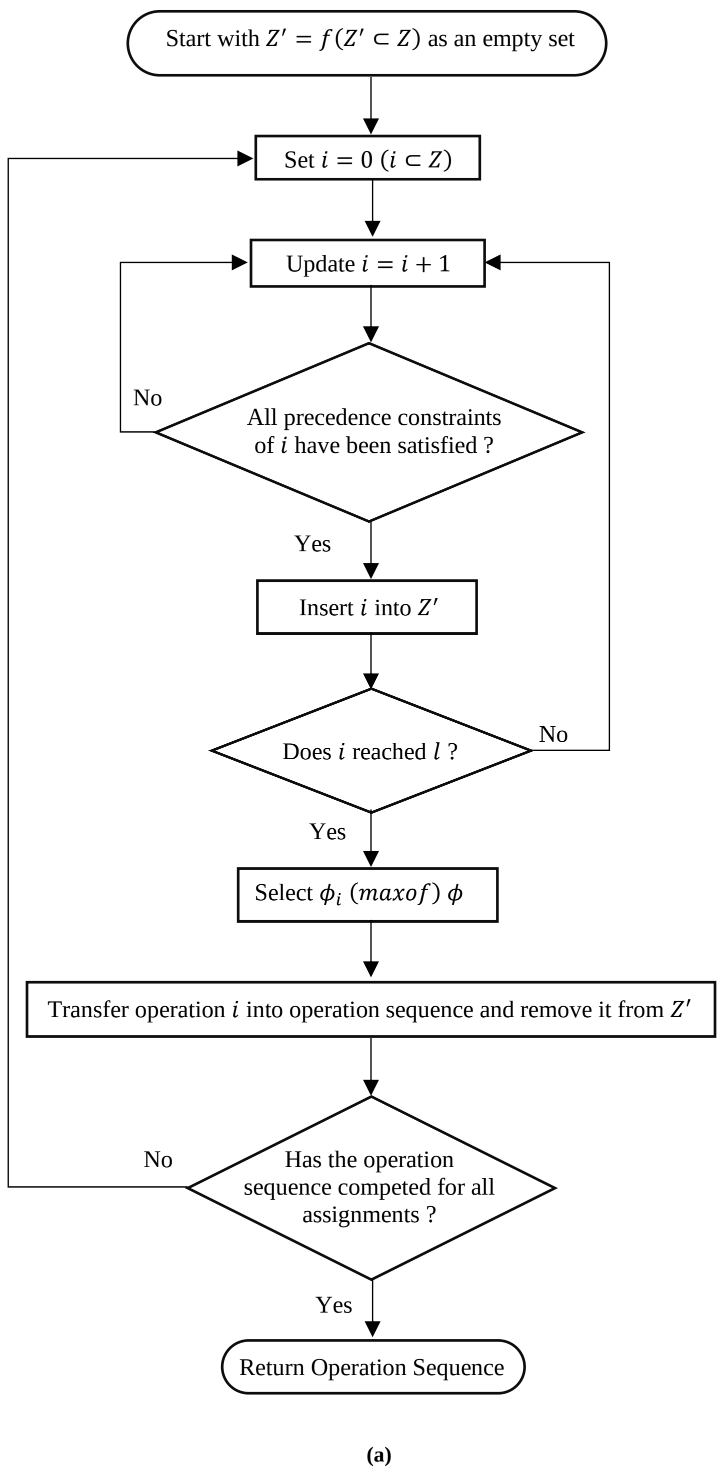


Fig. 3 Algorithm sequence for (a) Encoding and (b) Decoding

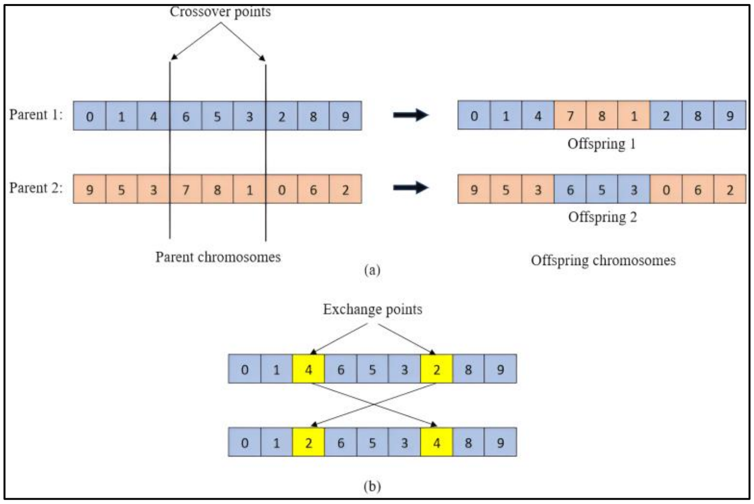


Fig. 4 Chromosome representation of (a) Crossover and (b) Mutation operators

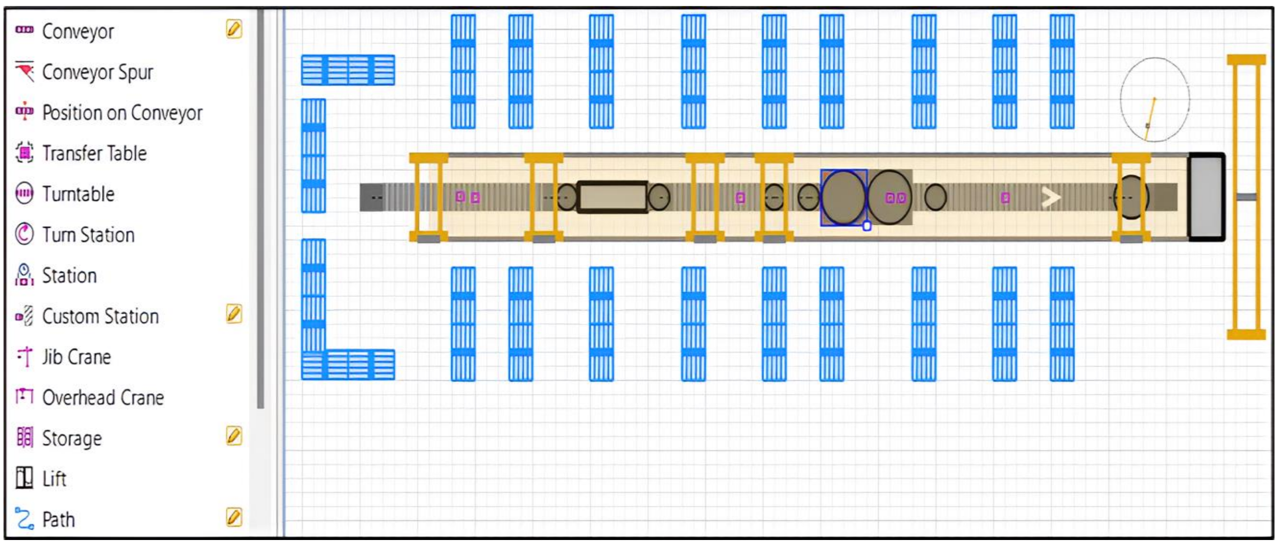


Fig. 5 Representation of assembly line layout in AnyLogic© software

5. Discrete Event Simulation

A discrete event simulation or discrete flow simulation model was built with the help of AnyLogic© 8.8.4 student version multi-method simulation software. For developing process flow simulation, the management data related to cycle time, idle time, lead time, customer demand and so on was transferred into a model that allows performing virtual experiments to understand basic trade-offs and relations in process flow analysis with consideration of financial and operations KPIs (Key Performance Indicators). The basic representation of the physical front-end setup, along with different building blocks, is shown in Figure 6. Various work part transport methods such as type of conveyors, specialized workstations such as turnover devices, turntables, and transfer conveyors, as well as tooling and work part kitting options, including storage bins, overhead and jib cranes, were incorporated into the physical setup. This setup is to represent the flow of the line in terms of operation sequence and line layout.

6. Results and Discussion

6.1. Hypothesis Test for Cycle Time Variation

In the cycle time study of three models namely Model A, B and C, the variation in means of the cycle times of different models can be significant. In order to assess this, an Analysis of Variance (ANOVA) one-way hypothesis test was performed in the Minitab© statistical software for a sample size of 20 observations of each model.

The test was performed at a 95% confidence interval with Tukey method-based simultaneous comparison. The null hypothesis was assumed as there is no difference between the means of cycle times of various models. The alternate hypothesis was assumed as at least one model has a different mean of cycle times among all other models. It is shown in Table 3 that the p-value of the ANOVA test was 0.001, which is less than 0.05. Therefore, it was concluded that the alternate hypothesis was true, and the null hypothesis was rejected.

Further results of the hypothesis test, including means and grouping information at a 95% confidence interval, are tabulated in Table 4. Since the alternate hypothesis of at least one model having different mean cycle times was considered to be true, the grouping of models based on cycle time differences is shown in Figure 7. Since the interval of Model C and Model B lies outside the zero interval, the corresponding means were significantly different. Furthermore, the interval plot of cycle time versus model is shown in Figure 8, wherein pooled standard deviation was used to evaluate intervals. Hence, from the results of ANOVA, models A and C have significantly different cycle times. The results of ANOVA also helped in deciding the additional number of model flexibility stations required for high cycle time models.

Table 3. Result of one-way ANOVA hypothesis test

Source	DF	Adj SS	Adj MS	F-value	P-value
Model	2	259.4	129.69	8.26	0.001
Error	57	894.5	15.69		
Total	59	1153.9			

Table 4. Means and grouping information of hypothesis test

Model	N	Mean	St. Dev.	95% CI	Grouping	
Model A	20	51.28	4.72	(49.51, 53.05)	A	
Model B	20	48.462	4.333	(46.689, 50.236)	A	B
Model C	20	53.545	2.462	(51.772, 55.319)		B

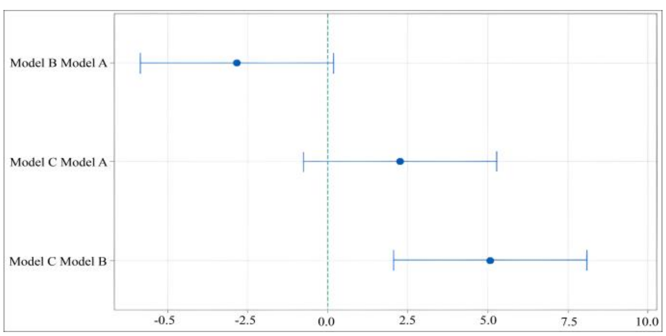


Fig. 6 Model grouping by Tukey comparison at 95% confidence interval

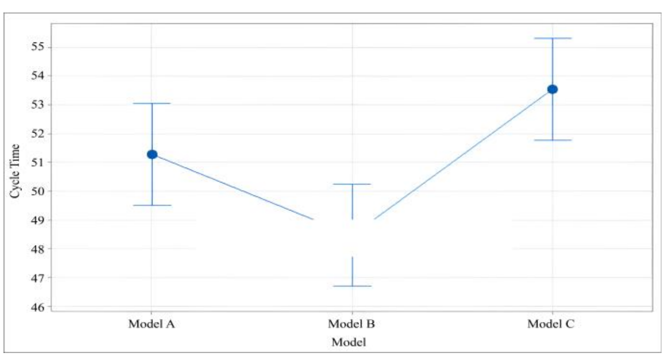


Fig. 7 Interval plot of cycle time versus model

6.2. Mixed-Model Assembly Line Balancing

While performing line balancing, the left and right side work contents were simultaneously balanced for each model; however, for ease of representation and interpretation, the model-mix balancing is shown independently for the left and right side in Figures 9 (a) and (b), respectively. In the RPW method, the ranked positional weights for each work element from 1 to 20 for models A, B and C were independently evaluated for left and right side work contents. Then, an assignment operation was carried out. While assigning operations to particular stations and grouping, both the weight of that element as well as position in the precedence constraint diagram were taken into account. The assignment was done by starting from the tip of the list according to RPW value, and elements were grouped at workstations until the condition. $T_{s_i} \le T_{s_{imax}}$ was satisfied. Then, the assignment was continued for subsequent workstations following the TAKT time requirement. All the work elements were assigned and balanced within 10 number of workstations as required. It can be seen from Figures 9 (a) and (b) that the workload has been balanced evenly across all assembly workstations without bottleneck, and the requirement of TAKT time of 61 minutes was satisfied. For models A and C, maximum workstation times of 56.74 and 57.08 minutes for the left side, whereas 55.25 and 57.08 for right-side work contents were observed. Least cycle times of 45.58 and 46.94 minutes were observed for Model A for left and right-side work contents, respectively.

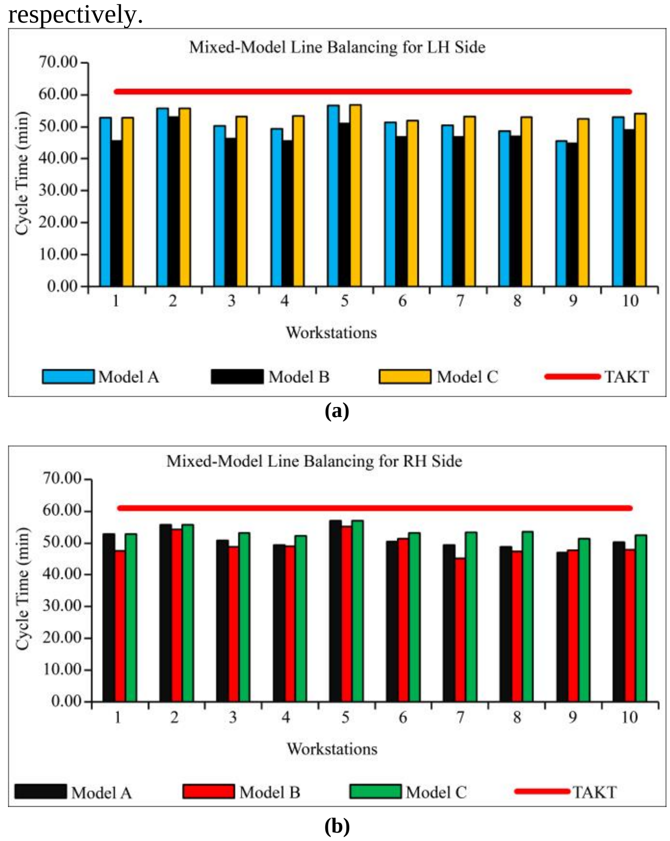


Fig. 8 Mixed-model line balancing for (a) left-side and (b) right-side work content

In line balancing results, apart from distributing the workload among a fixed number of assembly workstations, two more factors governing the overall performance of the line are discussed. The variation of dynamic rate of model launching with respect to changing demand and manpower or operator utilization. With increasing demand, the dynamic model launching rate tends to reduce following the trend of e^{-x}. However, with an increase in demand, the manpower utilization linearly increases. These both trends are shown in Figure 10. The combined manpower utilization against TAKT time for models A, B and C is shown in Figure 11. The maximum utilization of 93.29% and 93.44% was observed for models A and C at station number 5, whereas a minimum of 75.83% and 85.14% was observed at 9 for the same models. In the case of model B, a maximum utilization of 87.95% at station number 2 and a minimum of 75.90% at station number 9 was noted.

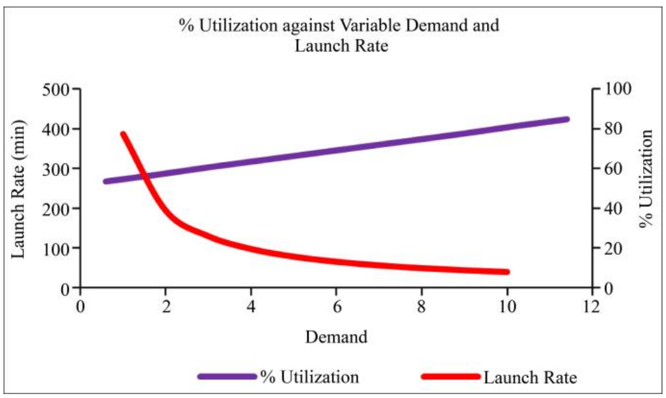


Fig. 9 Variation of dynamic launch rate and % utilization against demand

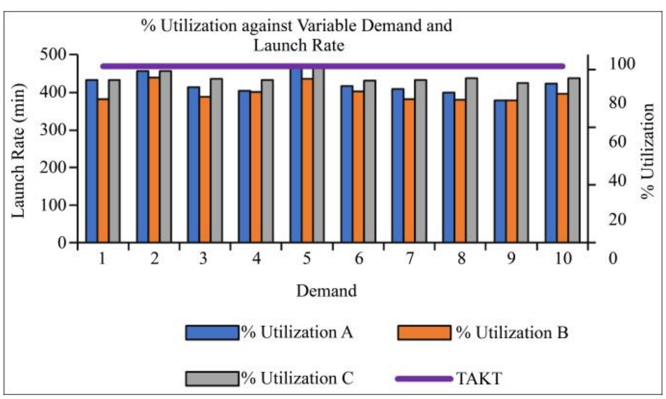


Fig. 10 % Utilization of manpower at each station against TAKT time

6.3. Discrete Event Simulation – KPI Analysis

The discrete event process simulation was used to create a simple model comprising four assembly stations, namely M1, M2, M3 and M4, at which the work part will be processed within TAKT time. The model contains a starting point as the source node and an endpoint as the sink node. The order arrival as per customer demand takes place at the source node, which is also explained as the base part launch rate in section 2. The orders will be processed at each station simultaneously and will wait if the capacity of a subsequent workstation is insufficient to process the assembly, which creates a bottleneck. Apart from this, four parameters were defined in the model namely start1, start2 and end1, end2. The point start1 defines the time at which the customer order arrives, and start2 represents the customer order dispatch time. The end1 and end2 take into account the time of order completion. Therefore, the time taken by the product to enter the value chain and leave the value chain after processing was calculated by “end1-start1”, which is also called manufacturing lead time. The flow time was measured as the time at which the order was dispatched and received by the customer was evaluated by “end2-start2.” The queue was added to the process flow to set the dispatch rules that are either FIFO (First In First Out), LIFO (Last In First Out), or priority-based in case of customer-specific orders. The process model is shown in Figure 12.

Furthermore, the results of discrete event process simulation were extended to design a productivity KPI (Key Performance Indicator) dashboard. The KPI dashboard contains the quantitative representation of various results such as workstation/machine utilization, cumulative capacity utilization, lead/flow time distribution, and mean and individual workstation-wise capacity utilization. These KPI results are shown in Figure 13, wherein workstation utilization of 99%, 51%, 96% and 31% has been shown for M1, M2, M3 and M4, respectively. The capacity utilization of the assembly line against TAKT time and running customer demand was obtained as half of the total capacity. In contrast, the mean utilization of capacity was evaluated to be 70%. The individual workstation-wise capacity utilization was observed to be 99%, 45%, 90% and 30%, respectively, for M1, M2, M3 and M4. The maximum and minimum lead time distribution was observed between the bands of 5% and 10%, respectively.

6.4. Computational Algorithm Results

The multi-objective two-sided mixed-model assembly line balancing optimization problem (MO-TSMMALBOP) was coded and executed in commercially available computational analysis software MATLAB® 2023a. The code was run on the system with Intel® Core™ i5 1135G7 CPU with a processor of 2.42 GHz speed and 8.00 GB (7.75 GB) usable RAM. The algorithm was run for 10,000 generations based on the problem definition and demand arrival scenario considered. The MO-TSMMALBOP algorithm was converged to the pareto front solution from the initial generation of the population to the final 10,000th generation. The convergence or stopping criteria for iterations of algorithms were defined in such a way that the code will iterate till the best-fit solution has been repeated for 50 generations without any improvement. The operating parameters of genetic algorithm code, such as population size, crossover, mutation, and reproduction were set to the values of 200, 0.9, 0.20 and 0.08, respectively.

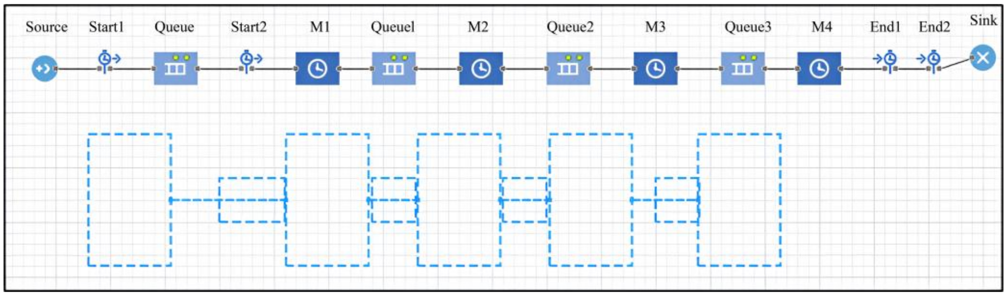


Fig. 11 Process flow model in discrete event simulation

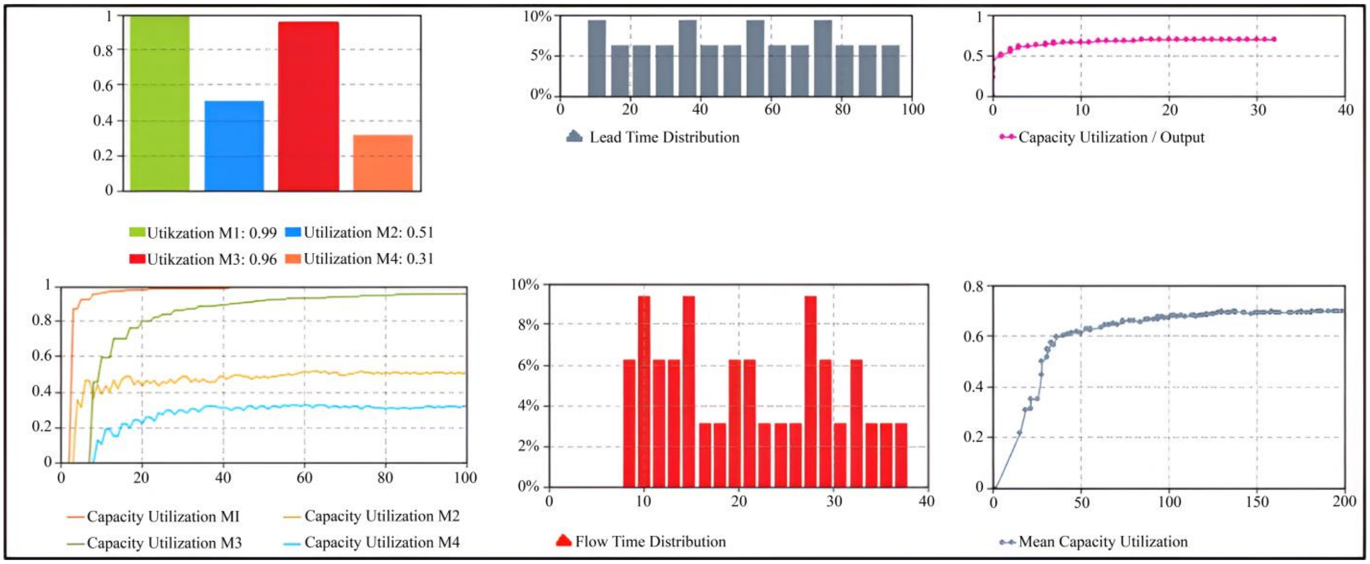


Fig. 12 Productivity KPI dashboard design for process simulation

Table 5. Results of genetic algorithm for different sets of problems test cases

Size	Model	Cycle Time	Optimized MO-TSMMALBP	
			n	WO
Small	AV281	9	6	0.1667
	BV282	12	8	0.1256
	CV283	11	7	0.0971
	DV284	15	9	0.0566
Medium	EK381	21	10	0.2148
	FK502	25	13	0.0369
	GK504	22	11	0.1457
Large	HQ601	28	14	0.0197
	YQ604	32	16	0.2214
	ZQ781	30	15	0.0321

The best-fit solutions of the genetic algorithm were reported in terms of minimizing the number of required workstations 'n' and work overload 'WO.' The results presented in Table 5 below consist of sets of problem cases and their corresponding solutions. It was observed from genetic optimization results that, for models with unique identification codes given while data collection from the shopfloor for the study problem, the possible optimization of two variables, namely the total number of workstations and work overload, has been presented by their test size that is small, medium, and large categorisation. The categorization of models was done depending upon their actual cycle times evaluated based on MOST and stop-watch-based time study. However, while solving the optimization problem, the maximum number of workstations allowed was kept at 15 because high cycle time models were considered to generate feasible GA solutions. In the case of the analytical model presented in the earlier section, the maximum number of allowed workstations was evaluated to be 10 as only small to medium cycle time models were considered for line balancing.

7. Conclusion

The work presented in the paper concludes by quantitatively discussing the approach of analytical modelling of a two-sided mixed-model assembly line and the corresponding balancing problem. The complexity of an assembly line balancing problem discussed in the presented work arises due to the addition of work elements from both sides as well as the stochastic nature of model demand. It was discussed and shown that the new model or base-part launching rate varies as a function of the cycle time of the model for single/batch model assembly lines. In contrast, for mixed-model large assembly systems, it varies as a function of the work content of the ongoing or presently launched model at the starting workstation. In the presentation of line balancing of a mixed-model assembly line through the RPW method, practical scenarios of losses and utilization factors in terms of OEE and line balance utilization were taken into consideration. The balancing of work contents was done across 10 number of workstations and was kept fixed according to demand and TAKT-time calculations. The standard methodology of time-study or cycle time evaluation through MOST was discussed with the help of three basic models, which are utilized to segregate the operations into different sub-operations or tasks.

Subsequently, the results were discussed for the demand-supply framework-driven DES model generated through AnyLogic© software. The ability of discrete event simulation to correctly mimic the pace of the production line through mapping its productivity KPI parameters was presented. The quantitative analysis of KPI parameters, including flow time, lead time distribution, manpower utilization, and machine utilization, was presented through a process-driven simulation model. Furthermore, the optimization algorithm solution, MO-TSMMALBP, was presented for two objectives, namely minimize workstations and work overload.

The genetic optimization algorithm, which was run for a maximum of 10,000 generations, was converged to a pareto optimal solution with the appropriate convergence criteria applied. Further studies on this topic can be extended to the effective use of a predictive-modelling-based machine learning approach can also be made to develop a correlation between the mathematical model and discrete event model can be investigated for hybrid-flexible assembly systems.

Declaration of Competing Interest

The authors declare that there are no known personal relationships and competing financial interests that could have appeared in the data reported in this work.

Author Contributions

Rugved Patkar (Conceptualization; Formal analysis; Data visualization; Writing-original draft), Mahesh Ghanekar (Supervision; Resource availability; Project administration; Review), Sharnappa Joladarashi (Supervision; Review).

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